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FINAL REPORT

ACOUSTIC PROCESSING METHOD FOR MS/MS EXPERIMENTS

by

P. R. WHYMARK

INTERAND No. IC-726

FINAL REPORT

ACOUSTIC PROCESSING METHOD FOR MS/MS EXPERIMENTS

by

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Submitted by

INTFRAND Corporation
166 East Superior Street
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to

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George C. Marshall Space Flight Center
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ACOUSTIC PROCESSING METHOD FOR MS/MS EXPERIMENTS

I. INTRODUCTION

This report is the final report on Contract NAS 8-29030 entitled Acoustic Processing Method for MS/MS Experiments. The work undertaken has consisted of a six-month task to evaluate the feasibility of levitating and controlling the position of objects by the use of acoustic energy during manufacturing processes in space.

Over the past several years NASA has had an increasing involvement in the use of space for manufacturing operations. The feature of space flight which space manufacturing seeks to exploit is the extended free fall (low gravity) which makes possible many unusual manipulations of materials and alters chemical and physical processes. An important requirement in utilizing space for manufacturing purposes is the ability to control the position of objects. Without some form of position control suspended objects will tend to drift relative to the walls of the space vehicle making it very difficult to perform experiments and to process these materials. Hence the essential feature of the work undertaken under this contract is to study and evaluate acoustical methods in which intense sound beams can be used to control the position of objects. The position control, as we shall see later, arises from the radiation force experienced when a body is placed in a sound field.

In the report that follows we first undertake a description of the special properties of intense sound fields useful for position control. Then we proceed to discuss the more obvious methods of position control, namely the use of multiple sound beams. Following these discussions we treat the special case of a new type of acoustic position control device that has advantages of simplicity and reliability and utilizes only a single sound beam. Finally a description is given of an experimental single beam levitator, and the results obtained in a number of key levitation experiments.

Because of the wide applicability of the acoustic position control concept, we should understand that the use of sound energy for position control can be quite useful on earth under 1G conditions, as well as in space. On earth, bodies can be made to float without visible means of support and as such we tend to refer to this process as "levitation." A body may be levitated without precise position control.

II. PROPERTIES OF INTENSE SOUND FIELDS

As alluded to earlier, levitation and position control can be carried out acoustically by means of the radiation force that the sound exerts upon the object. This radiation force, however, can take several quite distinct forms.

In order to produce significant forces upon an object, such that the object could, for example, be levitated on earth prior to launch or drop tower testing, the radiation forces must be substantial. To obtain substaintial radiation forces (of the order of 500-1,000 dynes per square centimeter) we need intense sound fields. That is, sound fields of the order of 140-160 db sound pressure level are needed to levitate dense materials under 1G. Intense sound fields introduce another factor, namely that of acoustical nonlinearity in the gas in which the sound wave is propagating. As a result of nonlinearity a single frequency sound wave develops progressively into a shock wave after the wave has propagated a distance, so that errors can arise in interpreting experimental results if the sound wave is treated as having the same wave form at all times that the sound wave had at its source.

A useful advantage can arise from nonlinearity, however, in that the absorption of the sound energy is much larger when the sound wave is very intense than when the sound wave is of moderate amplitude at the same fundamental frequency. The increased sound absorption enables us to reduce the sound pressure very rapidly with distance from the source. In turn the force gradients acting upon the levitated body can be made quite large so that the restoring forces that return the body to equilibrium also are large. This increases the stability of the acoustic levitation. These factors are discussed in more detail in a later section. For the present we confine ourselves to a fairly detailed examination of the different types of radiation force that arises when a sound field interacts with an object. Note that the levitating sound field can be either "free field", i.e., no reflections, or a standing wave field in which reflections are deliberately

introduced. Acoustic levitations can often make use of standing waves to increase the radiation force.

A. Steady Radiation Forces

There are three principal sonic forces exerted upon a particle in a sound field.[(1)] These forces are: radiation force, Oseen force and Stokes force, all of which will cause an unrestricted particle to move with a unidirectional motion. For the purposes of levitation we can ignore the Stokes force that arises from viscous drag.[(2)] The Stokes force becomes of significant magnitude only when the particle is very small, i.e., of micron dimensions, which sizes are too small to be of interest in the levitation system.

For acoustic levitation we are left with radiation force and Oseen force. Here again, the Oseen force should be relegated to a special function, i.e., the levitation of bodies that are no greater than about one half of an acoustical wavelength in the gas. This puts the size of the levitated body to a few inches in linear extent though at low frequencies a body considerably larger could be made to experience significant Oseen forces (see later). If the levitated body is larger than a half-wavelength, the Oseen force tends to reduce to zero. We should note that the Oseen force can be considerably larger than the radiation force for small bodies. While the Oseen force is useful in developing large levitation forces on small bodies, the radiation pressure force is ultimately capable of levitating bodies of practical sizes in space processing,that could, conceivably, include bodies several feet in linear dimensions.

1. Radiation Force

To illustrate in as simple a manner as possible how radiation pressures arises[(3)] consider a layer of gas,close to a reflecting surface,that is alternately compressed and rarefied due to the incidence of a sound wave. If the gas layer advances half-way towards the reflecting surface the pressure is doubled, assuming Boyle's law to hold. If the layer moves an equal distance outwards from its original position the pressure falls, but only by one-third of its original value. If we suppose

the layer to be moving harmonically, it is obvious that the mean increased and diminished pressures is in excess of the normal value. This excess pressure is the radiation pressure.

This argument can be reduced to numerical terms using a simple treatment due to Larmor and Crandall.[4] The case considered is that of plane waves incident normally on a perfectly reflecting wall. The wall is pushed with velocity v to meet the advancing train of waves. The energy density in the incident wave-train of velocity c is E, and in the case of a stationary reflector the total energy density due to both incident and reflected waves is 2E. In unit time the length of the wave train incident on the wall is (c + v). On account of the approach of the wall, this is compressed into a space of length (c-v). Consequently, the energy density in the reflected wave is increased in the ratio

$$\frac{E+\delta E}{E} = \frac{c+v}{c-v} = 1 + 2\frac{v}{c} \qquad (1)$$

since v is very small, so that $\delta E = 2vE/c$

In a region of length c in front of the wall, the increase in total energy is therefore $c.\delta E = 2vE$. This must necessarily be the work done in compressing the medium. Consequently, if P is the radiation pressure the work done by the wall in unit time is Pv, so that

$$Pv = 2vE$$

$$\text{or} \quad P = 2E \qquad (2)$$

The radiation pressure is therefore equal to the mean energy density in the medium in front of the reflector.

These simple arguments bypass a fair amount of complicated mathematics, but are limited to plane reflectors. However, note that there are no restrictions as to how large the plane reflecting surface may be. This is a valuable observation in regard to the levitation of large masses. In the case of non-planar reflectors, such as a small rigid sphere, the radiation force, F, is given by:[5]

$$F = \frac{11}{18} \pi R^2 (kR)^4 \rho \dot{\xi}^2 \qquad (3)$$

where

R	is the sphere radius
ρ	the gas density
$\dot{\xi}$	the particle displacement measured at the sphere
k	the wavenumber $(2\pi/\lambda)$
λ	the sound wavelength in the gas

and $R \ll \lambda$

Equation 3 may be expressed:

$$F = \frac{11}{18} \pi R^2 (kR)^4 E \qquad (4)$$

For a large rigid sphere the radiation force is: (6)

$$F = \tfrac{1}{2} \pi R^2 E \qquad (5)$$

The most general equations for the radiation forces acting on a free floating compressible sphere of any radius in a planewave field are developed by Yosioka and Kawasima. (7) The radiation forces are shown plotted in Figure 1. For large values of R shown on this curve the radiation pressure approaches the value given in equation 5.

Summarizing, we have the following radiation forces, F, on bodies of different shapes and sizes, expressed in terms of:

$$F = \alpha E \qquad (6)$$

where α is a size factor

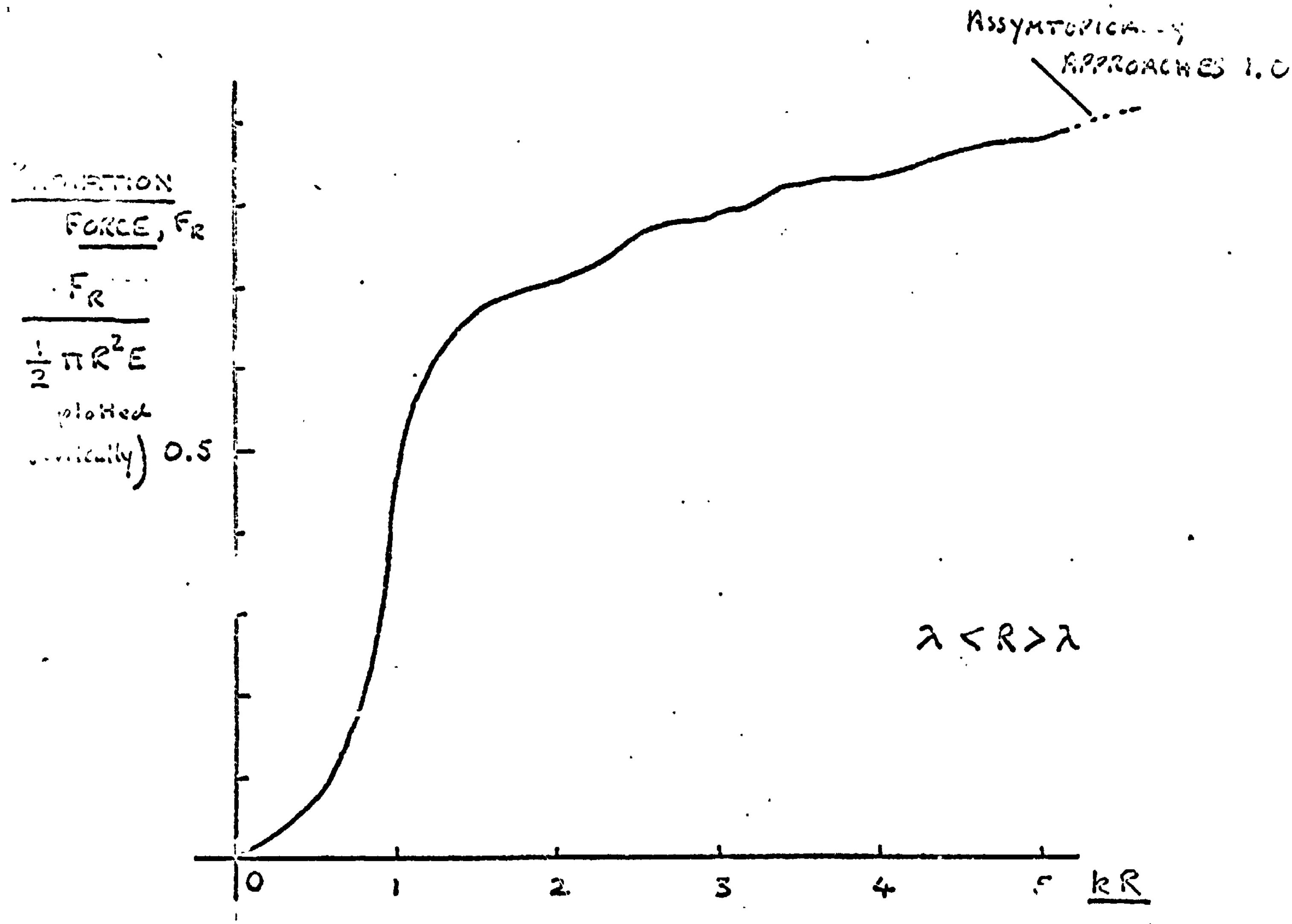

Figure 1. Radiation force on sphere of any size. An energy density, E, of 500 ergs/cm^3 gives rise to a radiation force of 750 dynes.

Reflector (levitated body)	Value of α	Comments
Plane surface	a	A = 1 for a perfect plane absorber
Small sphere	$\frac{11}{18}\pi R^2 (kR)^4$	a = area
Large sphere	$\frac{1}{2}\pi R^2$	Applied strictly to a rigid sphere. This condition is met by any solid sphere in a gas

The following numerical values of radiation force allow us to gage the practicality of the acoustic levitation system

$$I = Ec \tag{7}$$

Where I is the sound intensity at the reflecting surface

c is the velocity of sound in the gas

Generally, sound pressures in a gas of 160 db, or greater, are technically feasible. These sound pressure levels can be exceeded in a standing wave acoustical field.

160 db sound pressure $\simeq$ 1 watt 1/cm^2 acoustic radiation intensity.

For most gases (with the exception of hydrogen) c is about 3.5×10^4 cms/sec so that for a sound intensity of 1 watt/cm^2:

$$E = I/c = 10^7 \ (3.5 \times 10^4) = 286 \text{ ergs/cm}^3$$

For a plane reflecting surface, therefore, the radiation pressure given by equation 4 is 2 x 286 or 572 dynes/cm^2

For a 1 cm diameter sphere the radiation force is given by either of equations (4) or (5). The sound frequency used governs which equation should be employed. For purely practical reasons, concerning the ability to generate the intense sound waves, we know that the sound frequency should be greater than about 20 kHz and less then about 60 kHz. Taking a median frequency of 40 kHz the sound wavelength in the air is

$$3.4 \times 10^4 \ / \ 4 \times 10^4 = 0.85\text{cm}$$

Thus the 1 cm diameter sphere we wish to levitate is approaching the large sphere condition. The radiation force, therefore, on the 1 cm sphere, equation 7, is $\frac{1}{2}\pi.(0.5)^2$ 286 or 110 dynes. If the sound pressure is increased by 6 db this radiation force increa s fourfold. Thus the radiation forces we are dealing with range from a lower level of about 100 dynes to an upper level of about 500 dynes on the 1 cm sphere. Taking a median radiation force of 350 dynes the acceleration of the sphere, in low "g", is about 350/10 or about 35 cms/sec^2 assuming the sphere mass is about 10 gms. This acceleration is very adequate and indicates the small characteristic times involved in resto. . the position of a levitated body.

Note that the radiation force is always directed in the direction of travel of the sound wave. Also, even if the levitated body is irregular in shape there always will be a component of radiation force in the direction of wave propagation. The acoustic method is not limited to spherical or planar bodies.

2. Oseen Force

As alluded to earlier, the Oseen force is considerably larger than the radiation force for bodies small compared to a sound wavelength. However, the Oseen force is restricted to small bodies and is not of much use in the levitation of large masses. For the sake of completeness we include below a brief description of the Oseen force.

The Oseen Force arises basically from the waveshape distortion associated with large amplitude sound. This waveshape distortion takes the form of a progressive build-up of a sawtooth profile in a large amplitude wave, as the wave propagates further away from the source. If the body is smaller than a sound wavelength the rate of momentum transfer is greater during the steep portion of the sawtooth wave than during the slowly rising portion. This generation of the sawtooth distortion is discussed in detail in the next section. The different rates of momentum transfer lead to a net pressure proportioned to the degree of distortion of the wave.

Using an approximation derived by Oseen [8] the Oseen force, F_o, on a small spherical body is shown to be given by:

$$F_o = 3R^2 E c_2 \sin \varphi \tag{8}$$

where C_2 = fractional second harmonic distortion in the sound wave

φ = phase angle of the second harmonic

R = radius of sphere

For $\varphi = \pi/2$ and $c_2 = 0.5$

$$F_o = \frac{3}{2} R^2 E \tag{9}$$

Comparing the Oseen force with the small body radiation force given in equation (3) we can see that the Oseen force is several magnitudes larger. However, this advantage is lost when the body size becomes in appreciable fraction of a sound wavelength.

B. The Sawtooth Wave

At the sound intensities needed to produce acoustic levitation of dense materials, the particle displacements and sound pressures are no longer infinitesimal. In fact, in a very strong sound field, i.e., a 160 db sound field, the sound pressure is about 0.01 atmosphere. These sound pressures are very definitely finite and lead to a progressive build-up of a sawtooth shape in the wave profile as the sound wave moves further away from the source. Close to the sound source the sound profile is sinusoidal if the sound source is a pure harmonic vibrator. What happens in the sawtooth effect is that the crests of the sound wave travel faster than the troughs. This happens because the compressibility of the gas is appreciably smaller when the medium is compressed than when it is rarefied. An increase in pressure will cause the wave crests to travel faster and cause the sawtooth effect.

The importance of sawtooth build-up in levitation is that it provides a useful method for grading the absorption along the sound path to any degree we want. This allows tailoring of the spatial distribution of radiation force needed to obtain stable levitation in multi-beam levitators (see later). The tailoring of the absorption characteristics is possible because of the increased sound absorption that arises in finite amplitude waves.

The progressive build-up of a sawtooth sound wave is illustrated in Figure 2 in which the degree of distortion is expressed in terms of the parameter σ.[9] This parameter is given by:

$$\sigma = \frac{x}{L} \tag{10}$$

where x = distance of propagation

$$L = \frac{c^2}{\varepsilon \omega \dot{\xi}} \tag{11}$$

where

c = small amplitude sound velocity

ω = angular frequency

$\dot{\xi}$ = particle velocity at the sound source

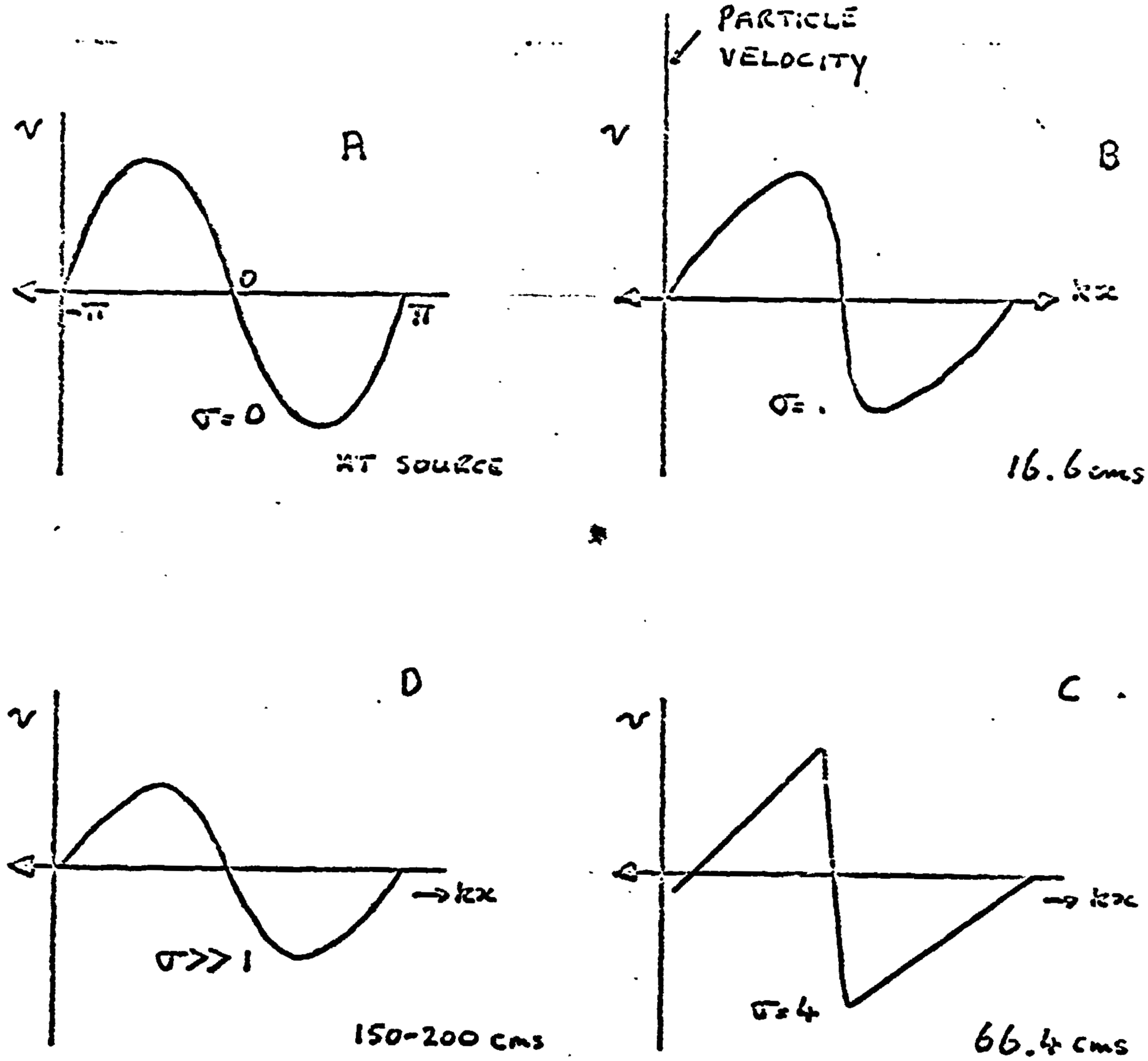

Figure 2. Progressive build-up of a sawtooth wave in an intense sound field. Parameter, J, expresses the strength of the source and the distance the wave has travelled. Distances shown are for a 160 db field at 20 kHz.

The parameter σ, is a measure of the distance from the sound source at which the sawtooth discontinuity becomes developed. For $\sigma = 1$, the sawtooth shape is well developed, Figure 2B; for $\sigma = 4$, the sawtooth shape is fully developed, Figure 2C, and shows a sharp discontinuity of pressure. Taking typical sound field values:

Sound field source intensity	160 db
Frequency	15 kHz
Sound velocity	3.5×10^5 cm/sec
γ	1.4 (monatomic gas)

Then $L = 50$ cms for the inception of sawtoothing of the sound wave ($\sigma = 1$). At 40 kHz, $L = 16.6$ cms ($\sigma = 1$).

C. Absorption Properties

An increase of the wave absorption in finite amplitude waves arises from the increasing steepness of the wavefronts due, in part, to stronger dissipation of energy as the velocity and temperature gradients grow larger. As a result, the wave absorption is dependent on the distance from the radiator, being small near the source, attaining a maximum in the region where the wave has a sawtooth shape, and then decreasing once again.

The Figure 3 shows the absorption of the fundamental and harmonics in a finite amplitude wave in air. At $\sigma = 1$ on the horizontal scale, the sawtooth is developed. This corresponds to a physical distance of 16.6 from the sound source for a 160 db source intensity at 40 kHz. The lower curves in the figure show the absorption of the harmonics in the sawtooth wave. In a practical case, therefore, the wave fundamental reduces by about 50% in travelling a distance of 50 cms. These distances can, of course, be scaled to suit the size of the particular space treatment chamber. Reducing the source sound intensity reduces the particle velocity and hence reduces the value of σ at a fixed distance. Thus the absorption rate is reduced with reducing sound intensity. This has the effect of reducing the restoring force on the levitated body since the radiation force will also show a smaller change with distance.

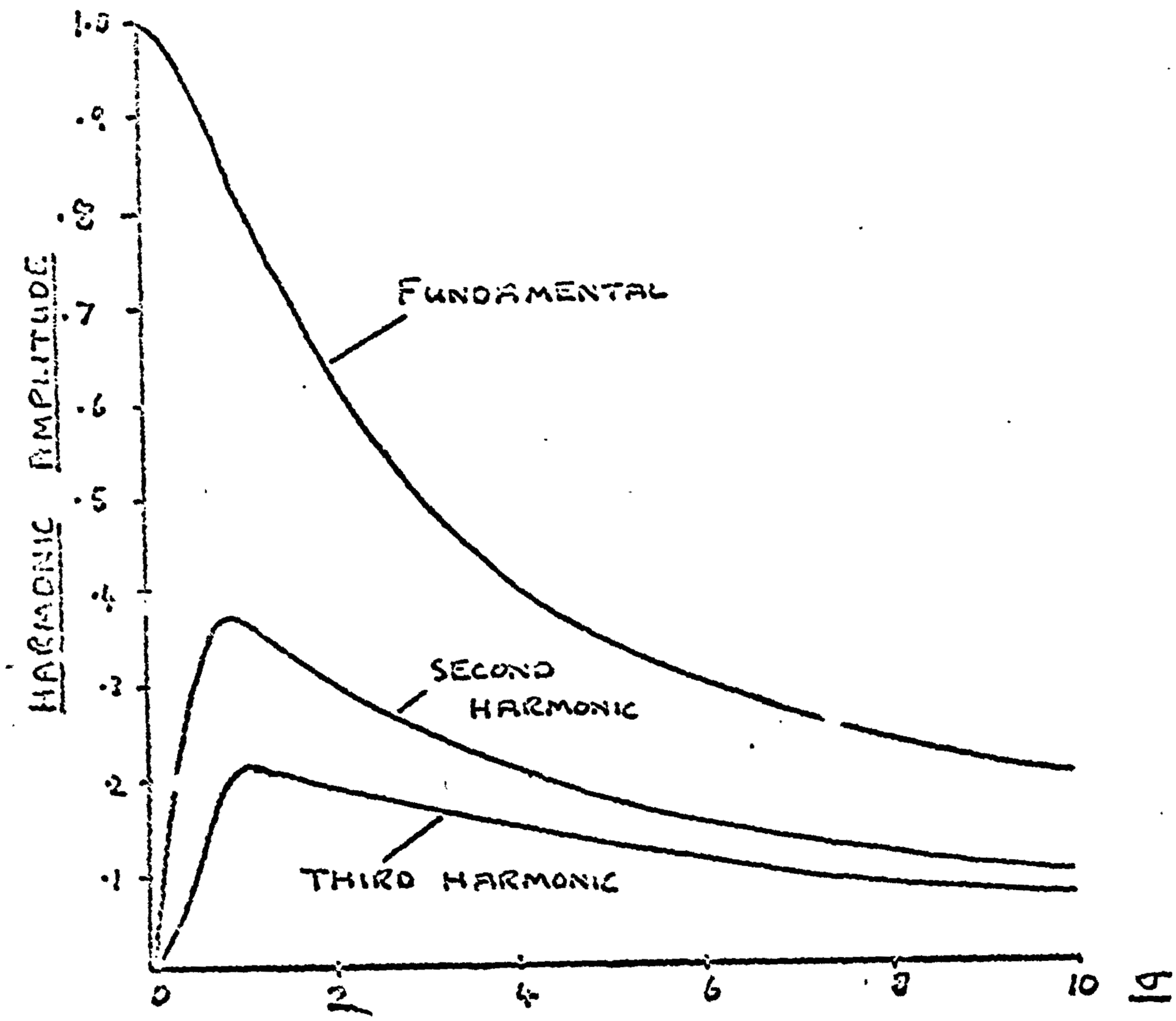

Figure 3. Amplitude of fundamental and harmonics versus distance. For $\sigma = 1$ the distance equivalence is 16.6 cms in a sound field of source pressure 160 db. Shape of the fundamental curve can be varied by changing the source strength.

The diagram, Figure 4, shows the effect on radiation force of increasing the intensity of two sound sources aimed at each other (see next section for one dimensional levitation). The change in restoring force on a levitated body, produced by a change in intensity can be clearly seer from the curves. Of course, when the sound intensity is reduced the radiation force reduces anyway. The significant point is that the space gradient of the radiation force can be tailored to fit the degree of restoring force required. The characteristic magnitudes of the radiation force appear to be appreciably larger than needed for effective levitation. Key factor is how well we can reposition the sphere and at what rate. This will depend upon the rapidity of space change of the radiation force. Hence the ability to tailor the force distributions via the large amplitude absorption process is an important feature in controlled levitation

D. Chamber Absorbers

The principal function of an absorptive lining in the space treatment chamber is to reduce the reflected energy sufficiently so that the reflected waves do not introduce significant spurious forces on the levitated body. Because the radiation forces are proportional to the square of the reflected wave pressure amplitude, small amounts of absorption will be sufficient. Furthermore, the high acoustic frequencies we contemplate using are such that most absorbers show a considerable suppression of the reflected waves. A fiber glass panel, one inch thick, used at room temperature, will show a 40 db reduction in the reflection of a 160 db wave at 20 kHz. In any possible high temperature applications, fiber metal absorbers can be used effectively. These absorbers can be formed in any metal and already have shown good absorptive properties in other high temperature environments such as acoustical linings for jet engine exhausts. In the limit, sufficient absorption could be obtained by lining the chamber with a thin, metal, perforated sheet.[10]

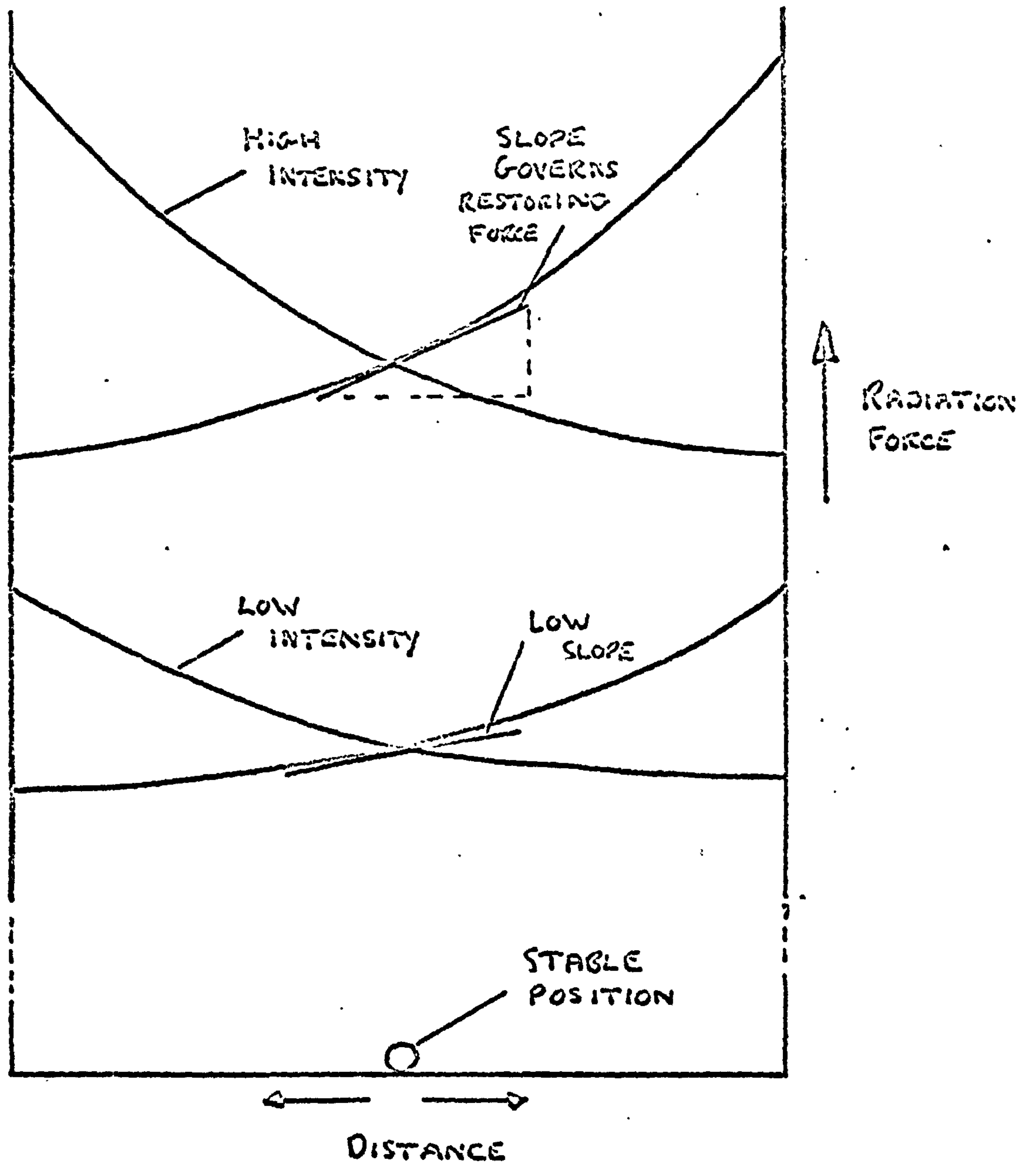

Figure 4. Effect on radiation force of increasing the intensity of the sound sources. The position of stability is unchanged but the restoring force reduces with intensity.

E. Diffraction and Scattering

Generally speaking, diffraction and scattering of the sound from the levitated body will be unimportant in 3-space levitation. The sound beams used are oriented at an angle to each other, so that shadow zones caused by the levitated body obstructing the sound will not introduce any adverse effects. Even in the worst case of colinear sound beams, the effect of diffraction can be negated. The illustration in Figure 5 makes this point clear. Scattering of the sound energy is handled by the chamber absorbers. Where any reflected waves cross the principal beams, the interaction effects are negligible, as alluded to earlier.

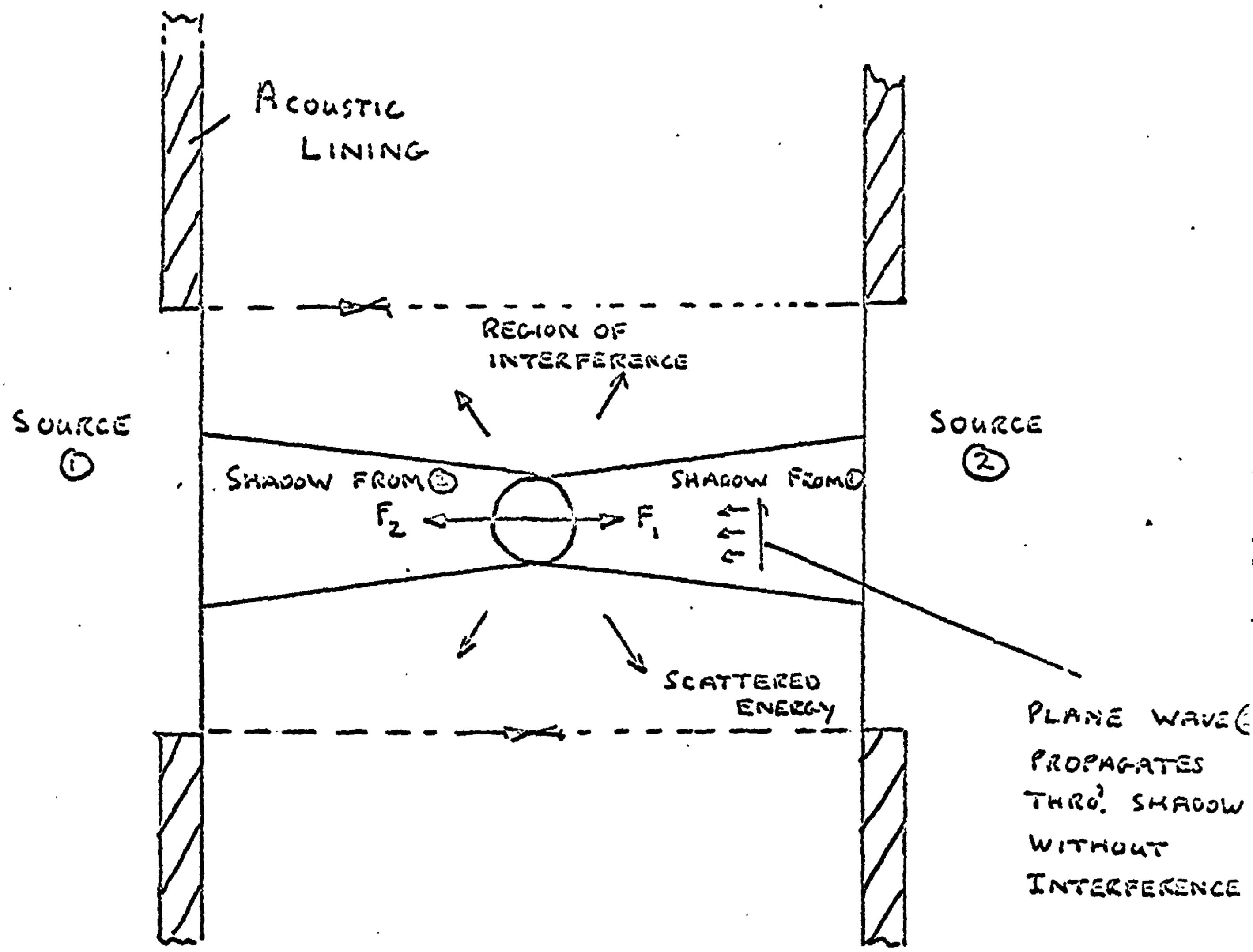

Figure 5. Effect of shadow zones. Interference will arise only outside of the sound shadows. Shadow zones are unimpôrtant with angled beams.

III. MULTI-BEAM ACOUSTIC LEVITATOR

The most direct method of levitating or controlling the position of an object using acoustical waves is by directing a number of sound beams at the object such that the resultant forces add to zero at the point where one desires to position the object. In the most obvious case, six sound sources arranged in pairs, each pair of sound sources beaming oppositely at each other along the edges of a cube would suffice to control the position of an object. We shall see later that the same objective can be attained by using four sound sources aligned in tetrahedral fashion.

The way the multi-beam levitator works is best understood by considering first a one-dimensional model.

A. The One-Dimensional Model

The object it is desired to levitate (a sphere in the example to be cited) is located in a roughly central position on the common beam axis of two oppositely directed intense sound emitters shown in Figure 6. Each sound emitter produces a narrow-angle sound beam directed at the sphere. The sound beams travel in opposite directions and the widths of the beams are several times the sphere diameter. This beam width allows the sphere to move laterally without passing out of the sound beams. The walls of the processing chamber are lined with a high temperature acoustic absorber shown typically at A and B, Figure 6. The absorbers absorb the energy scattered from the sphere and transmitted past the sphere.

1. Radiation Forces

Whenever sound energy impinges upon a surface a steady force is produced upon it. The nature of this radiation force was considered earlier. For the present, Figure 7 shows diagramatically two distributions of radiation force that may be produced along the axes of each of the two intense sound beams. These force distributions represent the force that the sphere would experience if the sphere were moved to different positions along the beam axes (the X axis in this model). The force fields from each emitter exhibit two principal characteristics: first, the forces are oppositely directed, and second, the forces reduce with distance.

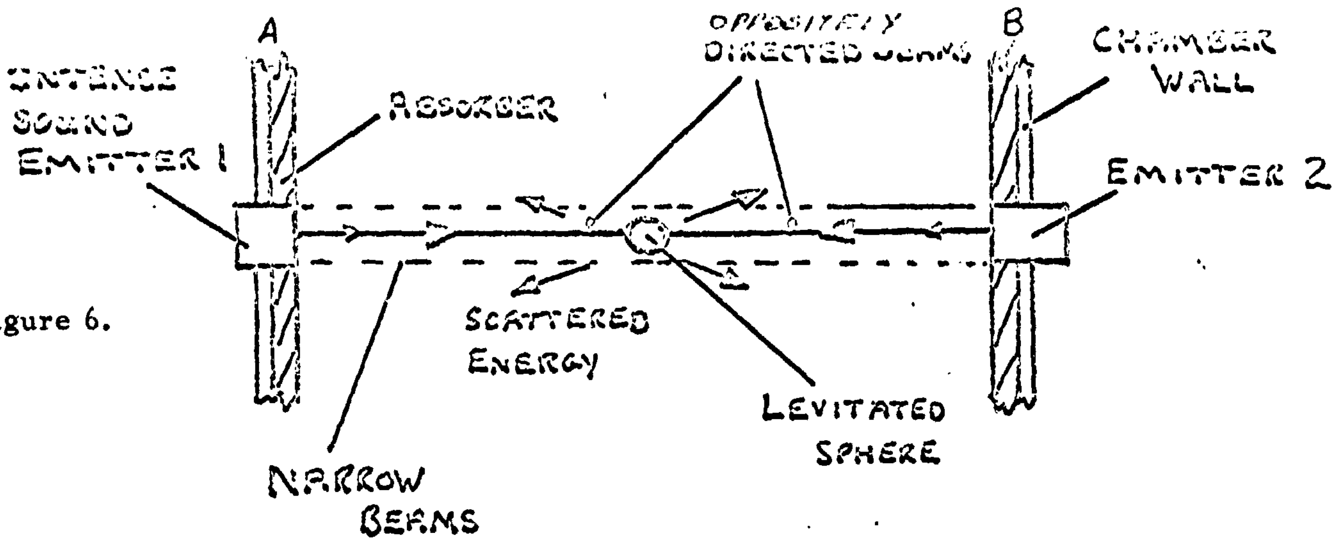

Figure 6.

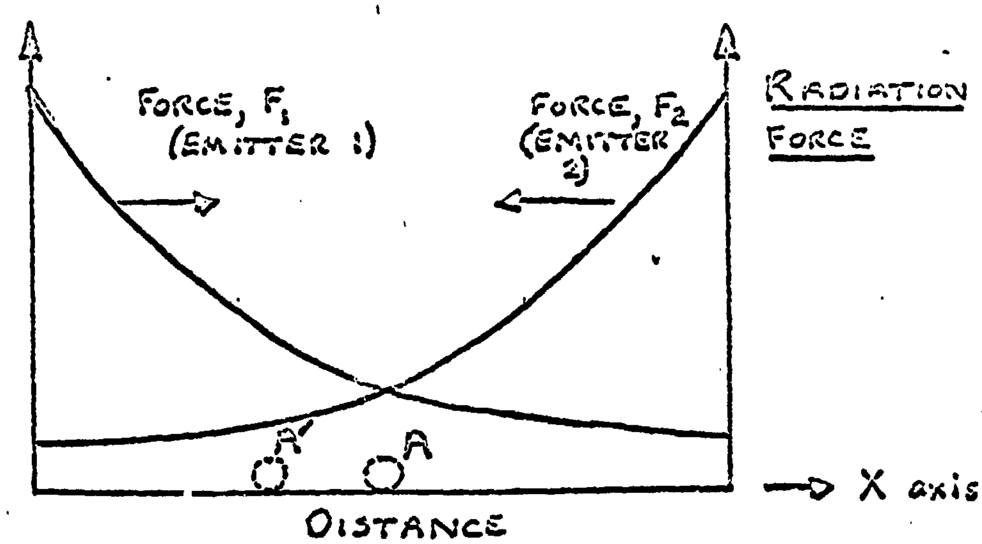

Figure 7.

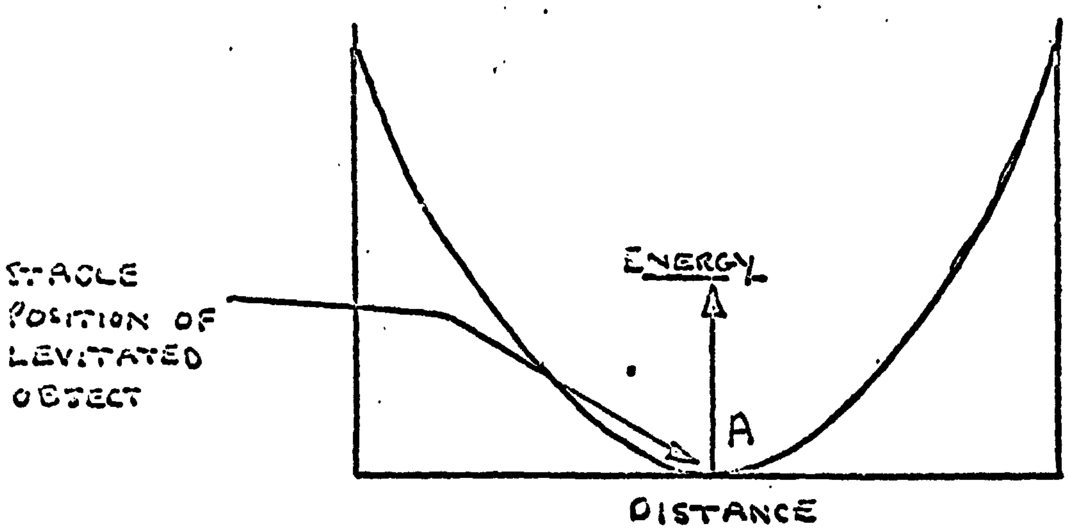

Figure 8.

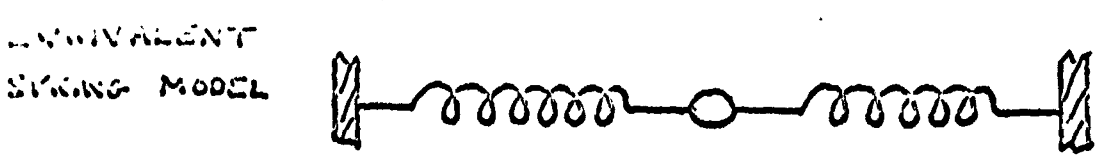

Figure 9.

LEVITATION SIMULATED IN ONE-DIMENSION

2. Energy and Stability

We are now in a position to understand how the sphere can be constrained by the two sound beams. Evidently, if the sphere is moved by an external force from the position A, Figure 7, where the force distributions from each emitter intersect, the work done by the external force is zero. It is proved in text books on statics that a body will be in equilibrium if the work done by the external forces in any small displacement is zero. Thus, the condition of a stable constraint on the sphere is met. If we extend this argument to 3-dimensions, the sphere would be levitated and be completely stable. Looked at from another viewpoint it is fairly evident that if the sphere is moved along the X-axis from a position A to a position A^1, Figure 7, the force F_1, from the emitter 1, will override the force F_2, from emitter 2. There is, therefore, a restoring force that will return the sphere to its equilibrium position at A.

Stating the stability condition in yet another way, the sphere will always move to a position of minimum potential energy. The distribution of potential energy corresponding to the radiation forces in Figure 7, is shown in Figure 8. Our sphere is in equilibirum at A. If displaced any distance within the potential well, the sphere will always return to equilibrium at A.

Of course, these arguments apply strictly only to stability in the plane through A normal to the beam axes. The sphere can come to rest anywhere in this plane. In our practical system the sphere will be completely constrained by using multiple beams covering the 3 space coordinates.

3. Harmonic Model

A moments reflection upon the distribution of radiation force, Figure 7 will convince the reader that these forces behave as though the sphere were held by two oppositely directed springs, Figure 9. Each spring provides a restoring force and acts very similarly to the oppositely-directed radiation forces shown in Figure 7.

Thus we can liken the radiation forces in our one-dimensional model as being equal to the restoring forces of two springs each of appropriate stiffness. Evidently, the sphere would exhibit damped simple harmonic motion if disturbed and released:

$$F = -kx$$

where F is the force

x is the displacement measured from the equilibrium position of the sphere

k is the spring stiffness equal to the gradient o radiation force

Furthermore, if the sphere is displaced and released, it will oscillate at a frequency f:

$$f = \frac{1}{2\pi}\sqrt{\frac{m}{k}}$$

where m is the mass of the sphere

We conclude from the preceeding arguments that the sphere can, in principle, be constrained to a given plane with complete stability. Furthermore, we have reduced the system to an extremely simple harmonic model for which the energy state and other factors are already well chronicled. The principle obviously can be extended to 3 dimensions to obtain the 3-space levitation desired.

4. Limitations to the Method

Naturally, if the sphere is not exposed to a sound beam the sphere will not experience a force. The sound beams must be large enough (about 10 cms diameter at the sphere) to encompass all reasonable spurious displacements of the sphere.

Another obvious question arises from the fact that the sound beams may tend to interact with each other. A classical example of this is a standing wave. However, beam interactions do not in fact limit the levitation method for several reasons. A treatment chamber, for example, may be acoustically lined so that multiple reflections of the sound energy will be avoided. Also, the sound beams will always be angled to each other and will not travel colinearly. In the case of angled sound beams

the only interaction between the beams is that which occurs where the beams cross each other. The sound beams influence each other only to a small extend and the effect can be shown to be exceedingly small.[11]

Restraints imposed by the geometry of the sound beams appear, therefore, to be small. Other possible limitations to the method such as the influence of the sound field on the molten metal itself are considered later. In all cases adverse effects of the sound are generally insignificant.

5. Overall Feasibility

The radiation forces set-up by moderate intensity sound fields are sufficiently large for rapid manipulation of the levitated body. A 150 db sound field, for example, in air, gives rise to a net radiation force of one hundred dynes on a 1 cm diameter metal sphere. This sound intensity corresponds to only 10 watts of total acoustic power in a circular-section sound beam of diameter 10 cms. The radiation force will move a 1 cm diameter metal sphere in Zero "g" about 30 cms in one second.

Substantial radiation forces will be set up whether the reflecting body is in the shape of a solid cube, sphere, or any irregularly-shaped solid.* Furthermore, the progressive field radiation forces are largely independent of the size of the body, providing it is larger than an acoustical wavelength in the gas. The wavelengths we shall be using will be of the order 1.0 cms so that most material can be extended to bodies considerably larger than the 1 cm diameter molten spheres mentioned in the purchase request.

* Note that bodies other than a perfect sphere will experience a torque as well as a direct radiation force. (See: Rayleigh, Text Book of Sound)

Fom the point of view of conducting tests in drop towers, the acoustical radiation forces are large enough to offset the residual "g" forces in free fall. For example, a 1 cm diameter sphere will have a net "g" force in free fall of about 10^{-2} x 9800 dynes (assuming the sphere weighs about 10 gms at rest on the earth's surface). The acoustical radiation forces can exceed 500 dynes on this sphere, or about a factor of 5 greater than the residual "g" force in free fall. In space, the acoustical radiation forces will completely override the gravitational forces.

B. Multi-Beam Acoustic Levitation System

The design of a practical multi-beam levitation system involves taking the one-dimensional system considered earlier and extending it to three dimensions. However, in doing this we need to convince ourselves that stability can still be achieved on the levitated object when the wave sound beams are made to cross each other. Also we need to consider the best position of the sound sources and what sort of force fields they develop.

1. Sound Source Positioning

The simplest form of emitter positioning for 3-space levitation is that in which the emitters are lined up parallel to the edges of a cube as illustrated in Figure 10. This set-up involves the use of a total of 6 emitters. However, this number of emitters can be reduced to 4 if the emitters are located at the apex and corners of a tetrahedron, Figure 11. The 6-emitter set-up is illustrated with each pair of emitters pointing at each other. This is done simply for clarity. It is evident that each emitter can be angled slightly so that the sound beams have no possibility of interacting. No interactions are possible in the tetrahedron.

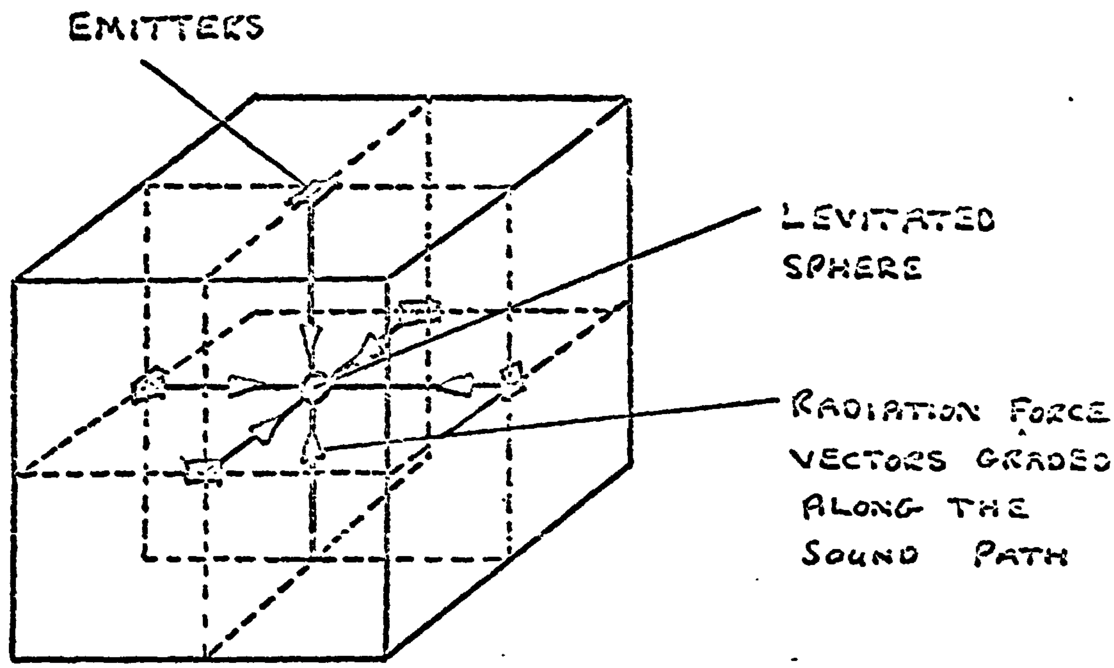

Figure 10. The 6-emitter system for levitation in 3-space. Sound beams are directed parallel to the edges of a cube.

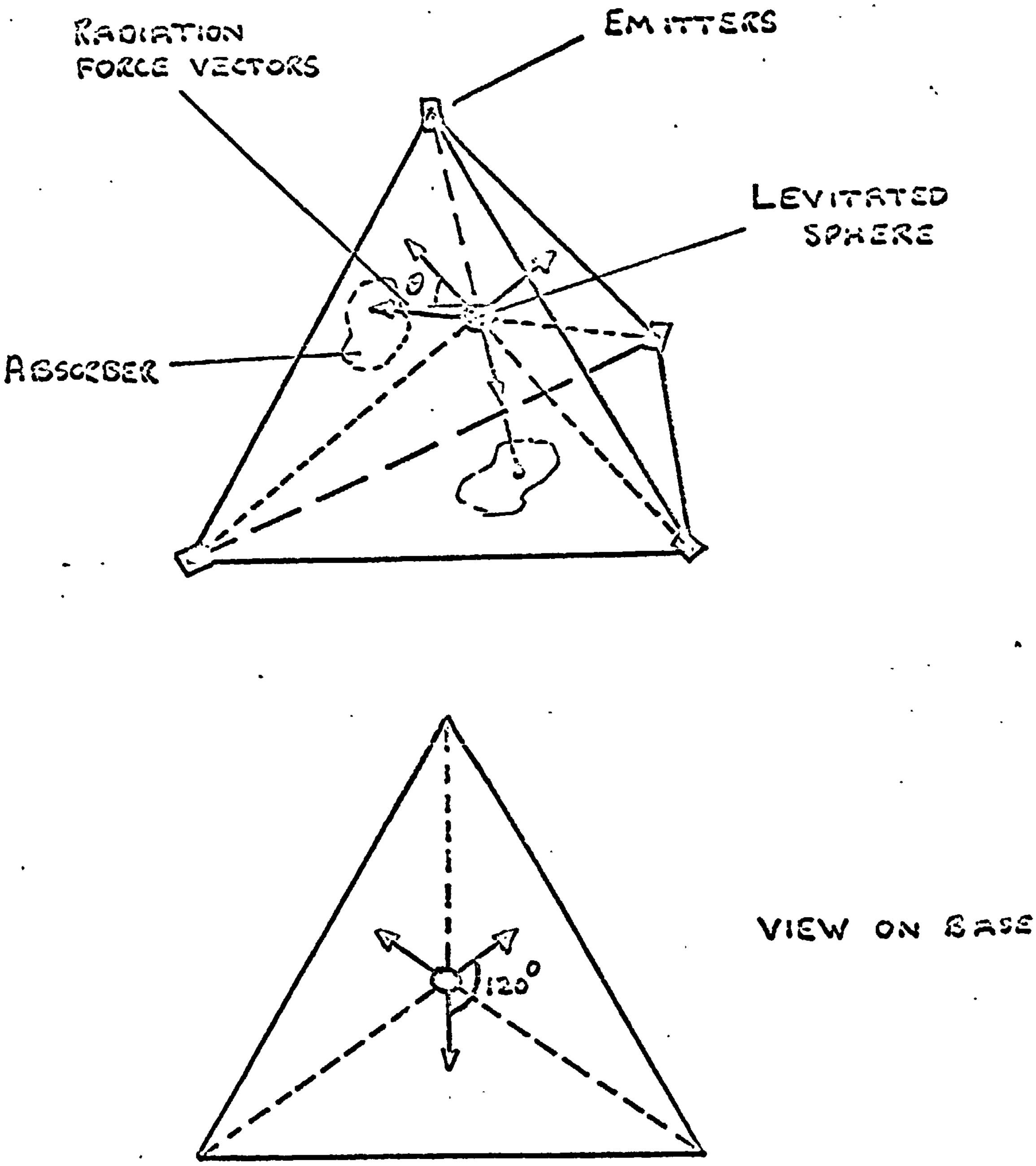

Figure 11. Emitters located at the corners of a tetrahedron. Stable levitation requires only the 4 emitters.

2. Force Field

The 6-emitter system is probably the simplest system to envisage. To obtain the force field around the levitated sphere, consider first the two dimensional situation illustrated in Figure 12. Four sound beams lie in the plane of the paper. For simplicity, the separate pairs of emitters are directed at each other. Assuming each sound beam is of equal strength the stability planes are at AA' on the X axis and YY' on the Y axis. The sphere is shown at the intersection of these planes along a line normal to the paper at C, representing the stable position of the sphere. Of course, the sphere is still free to move along this line but can be totally constrained by means of another pair of emitters beaming along this line

Referring again to Figure 12, we note that emitter 1 and emitter 2 produce a stability plane at BB'; the corresponding net radiation force distribution is shown towards the bottom of the figure. Similarly for emitters 3 and 4, that produce a stability plane at AA'. Now assume that the sphere is displaced to the dotted position at a distance r along a line at 45° to the beam axes. We now have two restoring forces acting upon the sphere - one along the X axis and the other along the Y axis. If each force can be expressed:

$F = K$ x's the coordinate distance

The X - directed restoring force $= K r \sin 45^{\circ}$

$= K r/\sqrt{2}$

$=$ y- directed restoring force

The total restoring force F_{TOT} on the displaced sphere is the vector sum of these forces:

$$F_{TOT} = K r$$

Applying similiar arguments to the case where the 45° angle is reduced to zero, i.e., to the case where the sphere is displaced directly towards or away from an emitter:

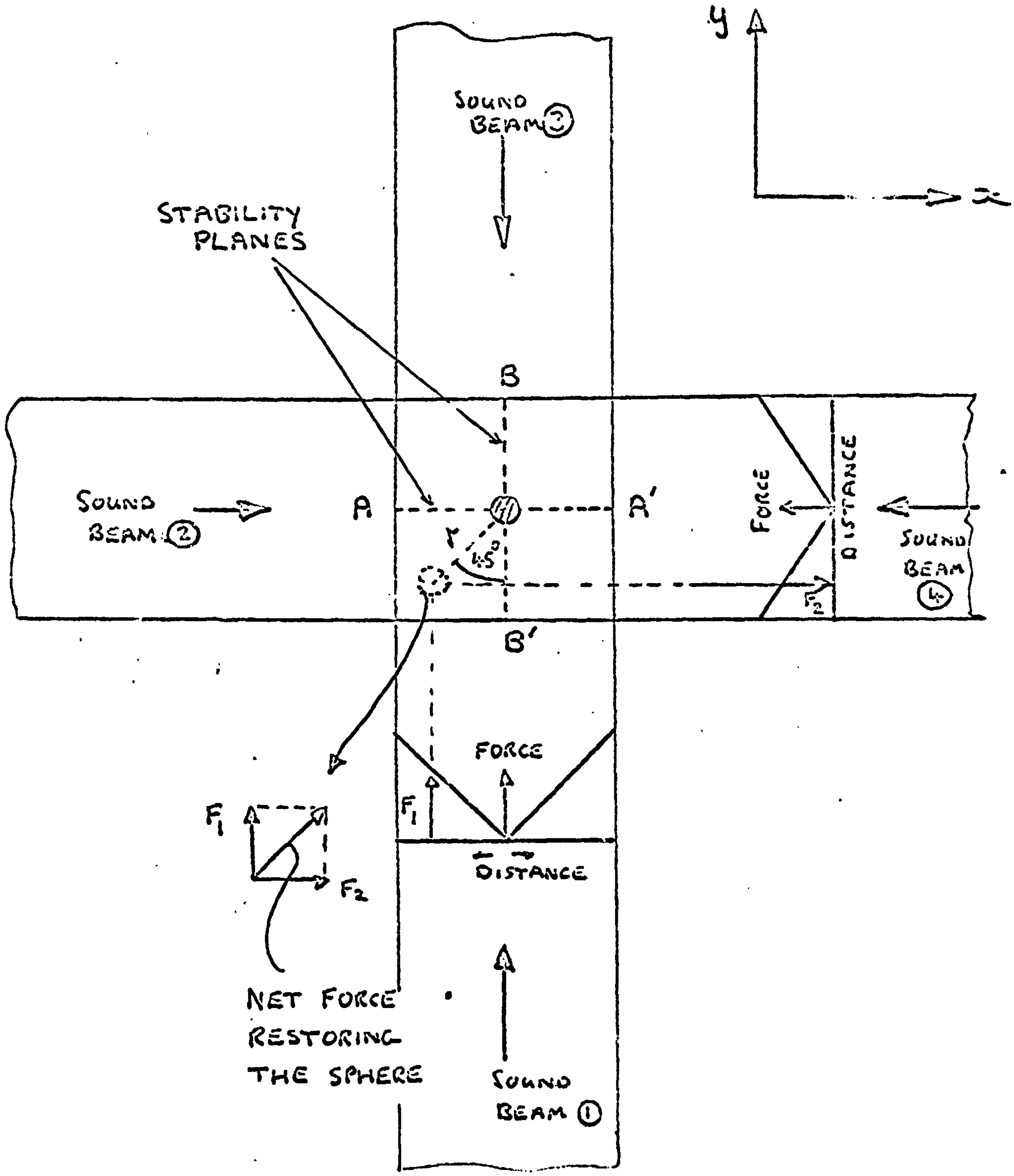

Figure 12. Restoring forces on displaced sphere in 2-dimensions.

The total restoring force is

$$F_{TOT} = K\sqrt{\;}/\sqrt{2}$$

We are thus able to plot the force distribution in two dimensions as shown in Figure 13. Evidently, whenever the sphere tries to move, there is a restoring force restraining the sphere to the central position at C. The system is thus completely stable.

This conclusion is exactly in line with that obtained for the one-dimensional model discussed earlier. Evidently, the above argument can be extended without any assumptions to the third dimension normal to the paper. In this case it is hard to plot the force distribution. Nevertheless, applying the previous reasoning it can easily be shown that the restoring forces along the beam axes, or at 45° to the 3 coordinate axes, are $3K\sqrt{\;}$ and $3K\sqrt{\;}/\sqrt{2}$ respectively.

We conclude therefore that the sphere will be completely stable in 3-dimensional levitation system.

The 6-emitter system can be considerably simplified by using the 4-emitter set-up shown earlier in Figure 11. The emitters are placed at the corners of a tetrahedron and each emitter beam is directed towards the sphere. The sphere is contained within the volume enclosed by the tetrahedron. This system differs slightly from the cube-system in that the emitters do not point at each other. A moments reflection will convince the reader that exactly the same stability arguments can be applied to this system as to the 6-emitter system. The radiation force from each beam can be resolved in any direction. Thus, the same stability arguments can be developed. For example, if the sphere is located halfway along the vertical axis of the tetrahedron and the separate emitters directed at it, each force vector acting upon the sphere will be at an angle $\tan^{-1} 4/\sqrt{3}\sqrt{2}$ to the horizontal plane through the sphere. If the sphere is located two-thirds of the vertical distance towards the apex, the force vector angle is $\tan^{-1} 3/2$. The sphere can be located at all points

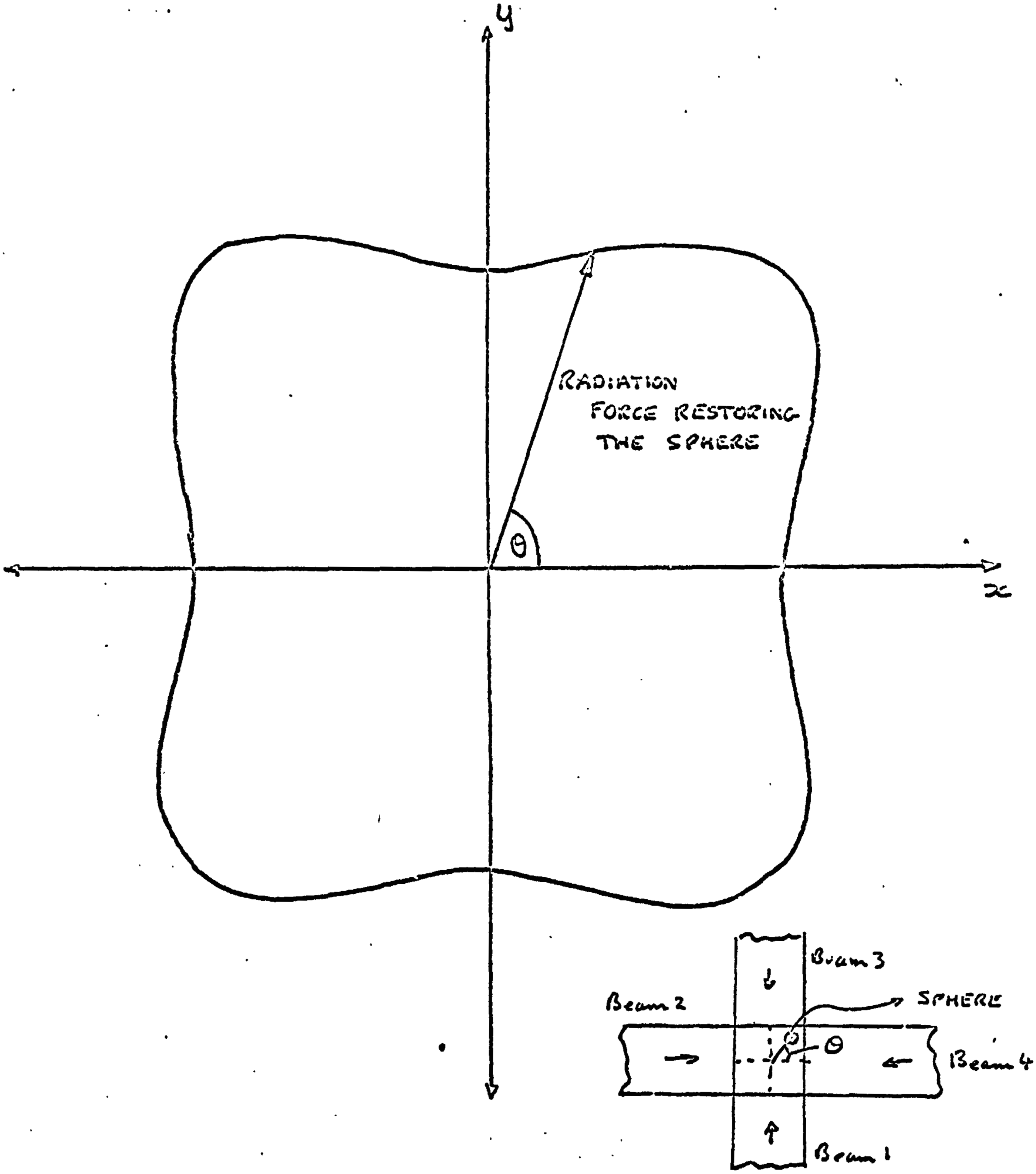

Figure 13. Stability diagram for 2-dimensions. The sphere will be restored to equilibrium wherever it lies in the beam intersection region (see insert).

within the tetrahedron volume. All that has to be done to adjust the emitters levels so that the null forces are produced at the point where it is desired to locate the sphere.

The tetrahedron model, therefore, results in considerable simplification and economy to the multi-beam levitation system.

However, the use of multibeams does result in a fairly complicated experimental configuration, and ideally some sort of zero control is desirable to insure that stability is maintained in the presence of random forces. A much more simple levitator is that described in the next section in which system only one sound source is necessary.

IV. ACOUSTIC ENERGY WELL LEVITATOR (SINGLE BEAM SYSTEM)

The single beam acoustic energy well levitator has received the greatest attention under this contract. The reason for this selection is that a simple and effective levitator is possible suing the single sound source and levitation stability is automatically obtained.

The acoustic energy well levitator consists of an intense ultrasonic piston sound source which is made to project a sound beam at a plane reflecting surface placed a foot or so away. The reflector is aligned with its plane normal to the axis of the sound beam.

The reflecting surface gives rise to multiple reflections of the sound energy between the surface of the sound source and the surface of the reflector. The resultant plane standing wave field has a succession of particle velocity nodes and alternate velocity antinodes distributed in parallel planes between the two reflecting surfaces.

Now it is a well established fact [12] that for a small dense body inserted into the standing wave a force is experienced urging the body to a velocity antinode. Looked at another way, the velocity antinodal planes in a planar standing wave field are planes encompassing the points of minimum potential energy. Thus a body will become levitated at these antinodal planes, assuming that the radiation force is sufficiently strong to overcome the "g" forces.

However, lateral constraint of the body is also needed, to prevent the body slipping sideways out of the levitating sound field. This lateral constraint is obtained in our single beam system by means of the potential energy minima that exist quite prolifically in the near field of the piston sound radiator.

The energy minima in the near field of a piston radiator are quite difficult to calculate for real sound sources, i.e., for sound sources that only approximate piston-like motion. However, techniques are available to present the near field energy minima, throughout the volume of the

near field, in facsimile form. Typical plots of the near field of a piston radiator are shown in the article by Hodgkinson (13). For a piston radiator about 20 wavelengths in diameter, several near field potential energy minima are shown, lying on the beam axis. This potential energy distribution is typical of the near field of all piston sources; the energy distribution is primarily dependent upon the size of the piston source in acoustical wavelengths. At the energy minima the levitated body will be laterally constrained and if a standing wave field also is established, as discussed earlier, stable levitation is attained in all three dimensions. The stability of the levitation process can be remarkably good (see "Experimental Results") leading to the conclusion that the energy wells are quite deep as well as having the spatial breadth indicated in the referenced article.

Experimental set-ups and the results of experiments are described in following sections.

V. EXPERIMENTAL ACOUSTIC ENERGY WELL LEVITATOR

The sound source used in the following experiments consisted of an electrodynamically driven,* half wavelength, cylinder of duralumun** resonant at 19.5kHz; the duralumun cylinder measured 3 inches in diameter and was 5 inches in length. A view of a typical sound generator is shown in the photograph Figure 14. Here, two generators are shown. The photograph shows the duralumun cylinder vibrator (front half of each generator) and the magnet used to drive the cylinder, shown at the rear section of each generator. The generators weighed about 6 lbs. each and the size of each generator can ge gaged from the 3 inch dimater of the vibrator. The weight and size of the sound generators can be reduced by about a factor of 5 to 10 by reducing the vibrator diameter to $1\frac{1}{2}$ inches.

* The generator was self-osciallatory so that no tuning was required.
** "Duralumun" - trade name for a high strength Mg-Al alloy.

Figure 14. Acoustic position control. The position of the sphere is controlled by sound beams emanating from the two generators.

At this point, it is worth commenting on the results of experiments using other equipment shown in Figure 14. Each generator is projecting an intense sound beam of 140 db sound pressure level along the axis of each vibrator, each beam being about 10° half angle. The beams are made to cross each other at an angle of about 90°. A plastic sphere ($1\frac{1}{2}$" D) is hung on a fine thread, and located at the intersection of the sound beams. Note that the sphere is pushed by the radiation force towards the right hand side in the photograph. This occured because the intensity of the LHS generator was increased above that of the other generator. A tendency was observed for the sphere to fluctuate when the sound intensities were changed; the sphere position fluctuated by about $\pm \frac{1}{4}$ inch to a 2 inch deflection from the undeflected position. This fluctuating motion could easily be dampened by attaching one end of a 1 inch length of 34 gage steel wire to the underside of the sphere and immersing the other end of the wire, to a depth of about 1/8 inch in light machine oil (note the oil dashpot shown in Figure 14 that served to provide the oil damping).

With oil damping, the sphere could be steered very positively in the horizontal plane to any position within a 6 inch diameter circle. The motion of the sphere followed changes in the intensities of the sound beams without any tendency to overshoot. No detrimental interactions occured between the 140 db sound beams. The conclusion from these observations is that no limiting difficulties should be experienced in extending the technique to 3 dimensional levitation using the 4 or 6 beam system alluded to earlier. Furthermore, it should be noted that each sound beam is operating in free field, without the gain in radiation pressure that would result if standing waves were allowed to be present (see earlier section). Also, note that this free field system is not limited to levitated objects of a particular size - the size of the object can be extended by any amount, but no advantage results if the levitated object becomes larger than the sound beam that intersects the object.

Figure 15. Levitation of a 3/16" D solid sphere inside a heater coil.

Figure 16. Levitated sphere. The sphere is located towards the center of the coil.

Figures 15 & 16 illustrate the results of levitation using the single beam acoustic energy well levitator. The electrodynamic sound source is located at the lower edge of each photograph and the single flat reflector is located toward the top of each photograph. The heater coil, towards the photograph center, will be discussed later. A styrofoam plastic sphere, 3/16 inch in diameter is shown levitated towards the center of each photograph. The levitation remained completely stable for indefinite periods. Insertion of the sphere was carried out by hand.

Attempts to dislodge the sphere from the energy well were made by pushing the sphere one inch or so off axis using a fine wire to deflect the sphere. On releasing the sphere, the sphere returned to its undeflected position and remained stably levitated* after a brief period of oscillation. The frequency of oscillation was about 1 hz from which frequency the restoring force was calculated to be about one fifth of the direct radiation force that was constraining the sphere to the levitated position. This calculation is approximate and could be in error by a 2 factor. However, it is clear that the magnitudes of the restoring forces are large (dependent upon the "depth" of the energy wells) and account for the high degree of stability observed in this type of levitator.

The coil shown surrounding the levitated plastic sphere in Figures 15 and 16, was for the purpose of simulating a heater configuration, surrounding the levitated object, in order to provide heating of the specimen. No effect on the levitation was observed with the open configuration of heater. When a closely wound heater was used, of the same size shown in Figures 15 & 16, the sphere ceased to levitate. On increasing the closed heater coil diameter by about a factor of 3 ($2\frac{1}{2}$ inch diameter heater coil) the sphere levitated quite stabily, even though the heater was the closed construction, offering substantial obstruction to the sound field.

* These effects are best observed in a movie taken during the course of these experiments.

Figure 17. Levitation of a 2" D metal disc. The disc can be of any shape.

Figure 18. Levitation of a 3/32" water droplet. The droplet is towards the RHS of the generator axis.

The photograph, Figure 17, indicates a slightly different version of the energy well levitator. A metal disc, about 2 inches in diameter and one sixteenth of an inch thick, is shown stably levitated about $\frac{1}{2}$ inch above the face of the sound generator. Again, the levitation process remained stable for indefinite periods. In this experiment the suspended disc is several sound wavelengths in diameter and weighs 2 to 3 ounces. The disc acts as its own reflector and automatically displaces itself from the exact velocity antinode to a plane within the standing wave system at which the net radiation force exactly equalizes gravity. In this sense the system is self-adjusting. This version of the energy well levitator is not significantly restricted by the size of the disc: The criterion of disc size, evidently, is that it should not be greater than the diameter of the face of the sound generator. Hence, using a battery of sound generators, aligned with their working forces in a plane, metal sheet several tens of inches in extent should be capable of being levitated.

The photograph, Figure 18, shows the energy well levitator, levitating a water sphere. The water sphere is about 1/8 inch in diameter and was inserted into the sound field by an ultrasonic atomizing process. The water drop oscillated from the equilibrium position by distances of up to $\frac{1}{2}$ inch. However, the water drop remained quite stably levitated.

Increasing the intensity of the sound field cause flattening of the water drop on the top and bottom sides. At this point, the radiation forces on the droplet are becoming a substantial fraction of the surface tension forces. The effect of sound pressure "flattening" can be used quite effectively to exert a degree of control over the shape of the levitated water drop, without touching the drop. Thus, the technique has obvious promise in nucleation studies.

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